

Science Fact

De revolutione scientiarum in 'media tempestas'

Michael F. Flynn

Note on format: Medieval Questions were arranged for publication into a standard format called the *dialectic*: 1) the **Question** to be determined; 2) the principle **objections** to the Question; 3) an **argument** in favor of the Question—traditionally, a single argument; 4) the **determination** of the Question after weighing the evidence; and 4) the **replies** to each objection. The determination is sometimes preceded by a **definition of terms** or by a **division into separate cases**. The determination was made before arranging the arguments.

Bibliographies were not provided, because the medieval philosopher *would have recognized an entire argument* from a brief quotation. A bibliography is provided here for readers not so blessed.

Question I.

The nature of the Scientific Revolution.

Article 1. Whether there was a Scientific Revolution.

Objection 1. *It would seem otherwise, because a revolution consists of definitive points of change, and is carried out during a short time according to a plan. But the development of science was continuous and unplanned.*

On the contrary, British historian Herbert Butterfield wrote that the Scientific Revolution "outshines everything since the rise of Christianity and reduces the Renaissance and Reformation to the rank of mere episodes . . . within the system of medieval Christendom."

I answer that "Science" is not simply an accumulated body of facts. It is a *methodology* for a) purposefully uncovering those **facts**, b) developing natural **laws** to describe them, and c) formulating physical **theories** to explain them. While the facts accumulate continuously, the methodology had, by the 17th century, undergone a radical transforma-

on involving six "innovative and essential features" identified by Peter Dear:

1. The view of the world as a kind of machine.
2. The distinction between "primary" and "secondary" qualities.
3. The use of deliberate and recordable experimentation.
4. The use of mathematics as a privileged tool for disclosing nature.
5. The pursuit of natural philosophy as a research enterprise.
6. The reconstruction of the social basis of knowledge around a positive evaluation of cooperative research.

Arguably, this revolution was confined to the physics of motion, but spread to chemistry a century later, to biology by the 1920s. (In practice, Darwin was a natural philosopher.) But a gradual sequel does not contradict a sudden advent. Science in our modern sense is only three hundred years old.

But how long was the pregnancy? Pierre Duhem argued that the continuity of the sciences with the medieval tradition was greater than humanist historians had supposed; but he based this on the "pre-discovery" of specific scientific laws like Newton's first law, a procedure subject to accusations of "cherry-picking." Whether Dear's *transformations* also had medieval roots will be explored in the Questions that follow.

Reply to Objection 1. That the Middle Ages contributed nothing to the history of thought is an *idée fixe* of the Modern Ages. Thus, as evidence grew for the medieval roots of much of the Scientific Revolution, so did the argument that there hadn't really been one.

But the Scientific Revolution was as "short and sudden" as the emergence of a butterfly from its cocoon. Those involved were purposefully engaged in overturning previous paradigms. Descartes' *Principles of Philosophy* is perhaps the "Storming of the Bastille." Yet, even if the "revolutionaries" were correct in their self-assessment, revolutions (and cocoons) always have deeper

origins. After all, it was never called the "Scientific Coup d'Etat."

"Tipping point" may be a better metaphor than "revolution."

Article 2. Whether the Scientific Revolution was uniquely Western.

Objection 1. *It would seem otherwise, because Western science grew from Aristotle's natural philosophy. Also, the ancient Greeks proposed atomism and heliocentrism, two themes of the 17th century revolution. Thus, the Scientific Revolution began in ancient Greece.*

Objection 2. *Furthermore, the West was backward compared to Islam, and learned of Greek natural philosophy through Arab intermediaries. Thus, the Scientific Revolution began in Islam.*

Objection 3. *Also, Shen Kua discussed magnetic declination and land formation by deposition and erosion; and maintained daily records of lunar and planetary positions. Thus, China also had a Scientific Revolution.*

On the contrary, Stanley Jaki has written that "the Scientific Revolution was stillborn in every other civilization."

I answer that while all peoples and cultures have accumulated "lore, skills, crafts, technologies, engineering, learning, and knowledge," Science is not the mere accumulation of facts. Those facts must be arranged and understood within the context of natural laws and physical theories. But scholars must believe that natural laws are possible before they will look for them. Obstacles to this belief have included:

a) *A multitude of self-willed gods.* There cannot be consistent natural laws if trees, rivers, and planets are capable of emotions and desires, and sundry gods can intervene in the world to contrary purposes. As Stock writes, "[the Roman's] daily experience led him to believe that nature's forces could be imitated, even placated; he was less sure they could be understood."

b) *The absolute autonomy of God.*

When even the act of handwriting is ascribed to God's direct intervention, "laws of nature" can be no more than "habits of God," and the reasons for them cannot be comprehended.

c) *An infinite sequence of cyclic universes.* If the cosmos and its mutations are eternal, all possibilities must eventually come to be, and "laws of nature" are merely temporary concatenations of little significance.

In the Latin West, these impediments were mitigated or absent. The Latins believed that the World has a beginning and an end (i.e., time has *direction*) and that a singular, rational God "disposed all things by measure and number and weight" (Wis. 11:21). By thus revealing His rational nature, wrote Anselm of Canterbury, and because He is faithful to His promises, God has bound Himself to act in a certain way. Such beliefs disposed the Latins to conceive a consistent World, knowable by "measuring, numbering, and weighing."

The Latins made a further, crucial distinction—between primary vs. secondary causation. As William of Conches wrote, "[God] is the author of all things, evil excepted. But the natures with which He endowed His creatures accomplish a whole scheme of operations, and these too turn to His glory since it is He who created these very natures." Later, Albertus Magnus [*De vegetabilibus et plantis*] wrote, "In studying nature we have not to inquire how God the Creator may, as He freely wills, use His creatures to work miracles and thereby show forth His power; we have rather to inquire what Nature with its immanent causes can naturally bring to pass."

They believed that their God had given material bodies the ability to act directly upon one another through their *natures*. Hence, *natural* laws. This "disenchanted" the World. There is no dryad behind the tree, no nymph in the well, only *natures* knowable to human reason. Further, since the heavens, too,

are just another created thing (Gen 1:1), and not, as the Greeks and others had supposed, something "alive, divine, and influential in human affairs," the heavens, too, must be governed by natural laws.

That the reasons for material phenomena should be sought in the natures of things, and not in the inscrutable Will of a transcendent Deity—and that these secondary causes are both consistent and rationally accessible—was a uniquely Western worldview.

Reply to Objection 1. The ancient Greeks invented the very idea of "science" (*historiê*, lit., "inquiry"), as well as "nature"—and without that none of the rest would have happened. (You can't have a Scientific Revolution unless there is already a science to revolve!) But *historiê* applied to nature was mostly a non-empirical speculative philosophy. Their criterion for truth was logical coherence more than correspondence to facts. Many, like Plato, doubted the reliability of empirical facts when they conflicted with a really cool logical theory.

Atomism and heliocentrism do not mark an ancient Greek Scientific Revolution for two reasons: a) being outside the mainstream of Greek thought, they *revolutionized* nothing; and b) they were not *scientific* in the modern sense intended here. They were not derived from empirical facts but deduced from logical necessity or assumed *a priori*. Democritus' *atomos* seems prescient only because we apply his term to a very different entity. His five "atoms" corresponded to the five regular solids and five "elements." ("Therefore," the element fire is painful because its tetrahedral atom has the sharpest corners.) Aristarchos placed the Sun in the center "because" fire was a nobler element than earth and rest a nobler state than motion. Aristotle and Archimedes, more empirical than most Greek philosophers, *rejected* heliocentrism because the predicted stellar parallax could not

be seen, thus "falsifying the theory."

Aristotle "lit the fire" of Science, although the fuse was uncommonly long. He organized a large body of empirical observations within a coherent philosophical framework, *making Science into a specific discipline*. This had a stunning impact, first on Islam, then on the West.

But Aristotelian natural philosophy, while necessary, was not sufficient: No scientific revolution occurred in Byzantium, which never had to discover or translate it. Few Byzantine scholars added to their heritage, Simplicius and Philoponus being notable exceptions. As Theodore Metochites wrote, "The great men of the past have said everything so perfectly that they have left nothing for us to say." Byzantium did, however, deserve its proud title of "The World's Librarian," and its preservation of ancient learning midwived both Islamic and Western science.

Reply to Objection 2. Initially, Islam treated Greek learning with greater enthusiasm than had the Byzantine Greeks themselves. However, no Muslim Aquinas ever reconciled Aristotle with Holy Qur'an. The great Islamic *fatwas* who embraced the Stagerite—e.g., ibn Sinna, ibn Rushd—embraced him all the way, becoming heretics to Islam. Those who rejected him—e.g., al-Ghazali—rejected him completely. The *fatwas* prospered only under the protection of powerful rulers; and their writings found readier audiences in Western Christendom than in Islam itself.

Islam denied secondary causation. According to Maimonides [*Guide to the Perplexed*], Islamic theologians asserted "when a man moves a pen, it is not the man who moves it; for the motion occurring in the pen is an accident created by God in the pen. Similarly the motion of the hand, which we think of as moving the pen, is an accident created by God in the moving hand. Only God has instituted the habit that the motion of the hand is concomitant with the mo-

tion of the pen, without the hand exercising in any respect an influence on, or being causative in regard to, the motion of the pen." Unlike Anselm of Canterbury, ibn Hazn claimed God need not even be faithful to these "habits." Al-Ghazali wrote in *Tabafut al Falasifa* [*The Incoherence of Philosophy*], "The imponderable decisions of God cannot be weighed by the scales of reason." Ibn Rushd countered with *Tabafut al Tabafut* [*The Incoherence of the Incoherence*], but in 1195 he lost all his offices and was exiled from Marrakech. As "Averrões," his popularity in Europe was second only to Aristotle, but little noteworthy science was created in Islam after his time.

"The problems of physics," wrote Ibn Khaldūn, "are of no importance for us in our religious affairs or our livelihoods; therefore we must leave them alone." An exception was the "practical sciences" of astronomy, medicine, etc., where Muslim scholars made outstanding contributions of *facts*. But *laws* of nature and explanatory *theories* smacked of men limiting God's autonomy.

At the dawn of the Middle Ages, Islamic science did outshine the Latin West; but by the close, their positions had reversed. Yet, without the Islamic translations and commentaries, modern Science would have been long delayed.

Reply to Objection 3. China had a scientific revolution in the 17th century when Jesuit missionaries introduced Western mathematics, heliocentrism, and . . . translations of Aristotle's natural philosophy. (That old Greek sure did get around.) Their revolution was the realization that there was such a thing as "Science." If the Muslims never had an Aquinas, the Chinese never had an Aristotle. They had never integrated the study of the natural world into a coherent philosophy, as Aristotle and his Islamic and European successors had done. Poetry, physics, gardening and alchemy were all *ko-chib*. In effect,

while the Chinese had *sciences*, they did not have *Science*.

Far from seeking causes in the natures of things, Chu Hsi argued that one should seek principles in the outside realm in only thirty to forty percent of cases; otherwise, moral principles should be sought within. Even this was too much for Wang Yang-ming, who criticized Chu Hsi's "externalist" views. Sivan described Chinese thought thusly: "Empirical knowledge is neither certain nor probable, merely given. . . . For certainty one looks to illumination, introspection, and other alternatives to purely cognitive processes. Certainty is, in the last analysis, a spiritual and moral stance."

The sages were more concerned with identifying the current point on the cosmic cycle than the natural causes of material phenomena. Sequence, frequency, quantity, and magnitude held little interest. Fang Yi-zhi [*Little Notes on Principles of Things*] wrote that sound and light "are always more subtle than the 'number' of things," i.e., than their measurement. Regarding heliocentrism, Juan Yuan wrote, "Our ancients sought phenomena and ignored theoretical explanation . . . It does not seem to me the least inconvenient to ignore Western theoretical explanations and simply to consider facts." If the Greeks valued logical theories more than facts, the Chinese prized facts with little concern for explanatory theories.

This "follow-the-procedure" approach had consequences. During the Huang-yu reign of Northern Sung, Shen Kua noted that candidates preparing essays on astronomical instruments "were so confused about the celestial sphere, and the examiners themselves so ignorant of the subject, that all candidates were passed with distinction." His proposal for daily records of planetary positions was sabotaged by his own staff, who simply made up the data.

Chinese arithmetical astronomy at its peak (AD 1300) had not achieved the ac-

curacy of Ptolemy's geometric astronomy a millennium earlier. Three centuries later, the Ming calendar "was regularly failing," yet the Directorate of Astronomy resisted Hsing Yun-lu's reforms—not on technical grounds, but as *sedition*. A public admission of calendar failure amounted to a declaration that the dynasty had lost the Mandate of Heaven, tantamount to a call for revolution.

Question II.

The medieval embrace of science.

Article 1. Whether the Middle Ages were an Age of Reason.

Objection 1. *It would seem otherwise, because the Middle Ages were the "Age of Faith," and faith is opposed to reason.*

Objection 2. *Furthermore, in the Middle Ages "ignorance [was] acceptable to God as a proof of faith and submission." Only in the Renaissance did Europe "awake, bathe, and begin thinking again."*

On the contrary, Adelard of Bath [*Quaestiones naturales*] writes, "It is through reason that we are human. For if we turn our backs on the amazing rational beauty of the World we live in, we should indeed deserve to be driven therefrom, like a guest unappreciative of the house into which he has been received."

I answer that the medievals valued reason so highly that they applied it to their own religious beliefs, and held God Himself to act reasonably. Both Renaissance humanists and Protestant reformers, for different reasons, accused the scholastics of *too much* reliance on logic and reason.

This Western fascination with reason grew in three stages. During late antiquity, Christianity had to deal with a living, dominant pagan philosophy. As Augustine [*De Genesi ad litteram*] wrote, "It is a disgraceful and dangerous thing for an infidel to hear a Christian, presumably giving the meaning of Holy Scripture, talking nonsense on [natural philoso-

phy]."

Later, in the cathedral schools, John Scotus Eriugena, Thierry of Chartres, Gerbert of Aurillac, and others taught from the Roman encyclopediasts and from the "Old Logic" of Boethius. Bernard Silvester laid out the lawfulness of nature, the taxonomy of the sciences, and the necessity of secular studies for Christian education.

Finally, the Latins discovered the natural philosophy of Aristotle. Not *re-discovered*. The Romans had never translated those books in the first place. (Boethius had begun the attempt, but had completed only some of the logic treatises before his execution.) Intrigued by references in the encyclopedias, the medievals flocked to Toledo and Sicily, once the jihad had ebbed, and learned Arabic and Greek to translate these works.

To be sure, Bernard of Clairvaux famously opposed Peter Abelard over the application of reason to matters of faith, but his was a minority position and was not a condemnation of reason itself. By the eleventh and twelfth centuries, logic and rationality had become "permanent and characteristic features" of the Latin West. Grant writes that this "widespread, conscious reliance on reason and reasoned argument seems to have had no counterpart in any other civilization about which we have any knowledge."

Adelard of Bath [*Quaestiones naturales*] summed matters up in this rejoinder to his nephew: "[T]he natural order does not exist confusedly and without rational arrangement, and human reason should be listened to concerning those things it treats of. But when it completely fails, then the matter should be referred to God. Therefore, since we have not yet completely lost the use of our minds, let us return to reason."

Reply to Objection 1. That faith is opposed to reason is a modern dogma accepted on faith. The medievals thought differently. Augustine had written [*Con-*

tra Faustum manichaeum], "In the Gospel we do not read that the Lord said: 'I send you the Holy Spirit so that He might teach you all about the course of the sun and the moon.' The Lord wanted to make Christians, not astronomers. You learn at school all the useful things you need to know about nature." Centuries later, William of Conches wrote [*Gloss on Boethius*] that the authors of Scripture "are silent on matters of natural philosophy, not because these matters are against the faith, but because they have little to do with strengthening it, which is what these authors were concerned with."

Reply to Objection 2. Modern impressions of the Middle Ages stem from the uncritical acceptance of distortions in the works of Luther, Galileo, Voltaire, and others. But Cantor writes that "[t]he image of the Middle Ages . . . at any given period in early modern Europe tells us more about the . . . intellectual commitments of the men of the period than it does about the medieval world itself." The myth of "a superstitious and credulous Europe giving way to a cool, rationalistic, scientific Europe" is a caricature. Remember, a millenarian panic occurred over Y2K, but not over AD 1000.

Article 2. Whether medieval philosophers were free to inquire into nature.

Objection 1. *It would seem otherwise because* Draper writes, "the Roman ecclesiastical system, like the Byzantine, had been irrevocably committed to an opposition to intellectual development. It crushed the mind."

Objection 2. *Furthermore,* in 1231, a papal commission was ordered to purge of error the works of Aristotle. And in 1277, the bishop of Paris condemned 219 Aristotelian propositions, many concerned with natural philosophy.

Objection 3. *Also* the Church taught the earth was flat, forbade human dissection, etc.

Objection 4. And what about Galileo?

On the contrary, Gregory IX [*Parens scientiarum*] wrote to the University of Paris that, excepting theology and canon law, "we grant to you the right of making constitutions and ordinances regulating the manner and time of lectures and disputations . . . who are to lecture and at what hours *and on what they are to lecture . . .*" [emphasis added]

I answer that only in the Latin West did Science find an independent, self-governing "home base" free of nearly all hindrances; namely, the Universities. Some of these developed from the earlier cathedral schools (Paris, Bologna), others from informal gatherings of scholars (Oxford, Cambridge). They possessed licensed faculties, standard courses, lectures, examinations and degrees, undergraduate and graduate studies, even the robes and funny hats we wear today. Their workings are described in Grant, Kibre/Siraisi, and Lindberg.

The late Berkeley chancellor Clark Kerr once said that about eighty-five medieval institutions "still exist today in recognizable forms, with similar functions and with unbroken histories." These include "the Catholic church, the Parliaments of the Isle of Man, of Iceland, and of Great Britain, several Swiss cantons, *and seventy universities*. Kings that rule, feudal lords with vassals, and guilds with monopolies are all gone. These seventy universities, however, are still in the same locations with some of the same buildings, with professors and students doing much the same things, and with governance carried on in much the same ways." They persevered through plague and war. It was one of Europe's finest achievements.

The use of reason was uniquely widespread in medieval Europe because the undergraduate curriculum consisted almost entirely of logic, reason, and natural philosophy. Arts and humanities were not taught. As today, most students settled into non-academic lives. Never be-

fore or since has such a significant portion of a population been educated so systematically in purely analytical disciplines.

Since the graduate schools of theology, law, and medicine required the undergraduate degree to matriculate, *nearly every medieval theologian had first been trained in natural philosophy*. This had important consequences for the acceptance of science by the medieval church. "Despite the 13th century controversies," writes Grant, "medieval theologians did not oppose Aristotelian natural philosophy *per se*. Even people like Bonaventure recognized its utility, and theologians in general were among its staunchest supporters." Indeed, many churchmen (Aquinas, Grosseteste, etc.) themselves pursued natural philosophy. Significantly, they did not cite dogma to demonstrate their conclusions, holding that an appeal to faith was not a philosophical proof.

Natural philosophers "pursued knowledge about the universe in a remarkably secular and rationalistic manner," writes Grant, "with little intervention from the Church and its theologians . . ."

Reply to Objection 1. Draper's polemic is not taken seriously by historians. Thirty-three of eighty-one medieval universities had papal charters, and another twenty had both papal and imperial charters. Chartering nearly two-thirds of all universities and allowing them to determine their own lecture contents seems an odd way of crushing the mind. *Parens scientiarum* has been called by some "the Magna Carta of the Universities."

Reply to Objection 2. The 1231 papal commission never filed a report and the expurgation was never carried out. The 1277 ban applied only to the University of Paris and was in place for only a short time. Aristotelian works were never banned at Oxford or elsewhere, save briefly at Toulouse. The ban represents an overreaction to a faculty dispute, not

a general attitude toward natural philosophy.

Some of the condemned propositions—[§154] “That philosophers are the only wise people in the world,”—speak for themselves. So does the so-called “double truth” that a proposition may be true in philosophy, but false in religion. The Church insisted that truth was singular, and if theology and philosophy disagreed, one or the other (or both) was not yet properly understood.

Many of the condemned propositions fall into a few repeated themes:

[§98] that the World is eternal,

[§49] that there cannot be a vacuum,

[§34] that there cannot be multiple Worlds,

[§140] that there cannot be attributes without substance (no “white” without a “white thing”)

Theologians argued that the universe did have a beginning (and would have an end). Also, since God could do anything short of a logical contradiction, anything that was not contradictory was at least possible and could not be eliminated *a priori*. In particular, God *could* have created a vacuum, and as many Worlds as He pleased. Thus, the World is contingent, not necessary, and natural laws must be learned through experience.

That attributes can exist without substance is the basis of the Eucharist—hence, the bishop’s objection—but it is also the basis of empty Newtonian space, which possesses the attributes of dimension without the substance of an extended body. (How can there be “length” without an “elongated thing”?)

The Condemnation marked the only major irruption of medieval theologians into natural philosophy, and had a paradoxical consequence. The Byzantines, Muslims, and Latins had encountered in Aristotle a fully articulated schema of mesmerizing scope and complexity. The Condemnation broke the spell. *The Stagerite might not have gotten everything right*. If he was wrong in theology,

might he also be wrong in philosophy?

Albertus Magus devoted a chapter of his *Summa theologia* to the errors of Aristotle: “Whoever believes that Aristotle was a god, must also believe that he never erred. But if one believes that Aristotle was a man, then doubtless he was liable to error just as we are.” The notion grew, writes Wallace, that “Aristotle’s views had to be examined critically, corrected, reformulated, and sometimes rejected entirely, not only when they conflicted with theology, but also with the manifest data of experience.”

No great spurt of non-Aristotelian thinking—dare we say “null-A”?—followed immediately after 1277, but philosophers gradually began to reason, *secundum imaginationem*, regarding the possibility of void space and motion through it, of multiple worlds, and so on.

By empirical observation, sublunar spaces are “stuffed” with earth, water, air, or fire. So Aristotle reasoned that the heavens were stuffed with an aether. Motion is the ratio of force to resistance; a void lacks resistance; therefore, motion in a void would be instantaneous—an impossibility. QED. “Empty space” (hence, Newtonian mechanics) is impossible to an Aristotelian.

But Walter of Burleigh reasoned from Eucharistic doctrine that empty space was possible. Bradwardine dismantled Aristotle’s model of motion using compound fractions and a new idea: “instantaneous motion.” Buridan found the aether unnecessary and concluded that motion in a void was finite and would continue indefinitely unless opposed. Albert of Saxony determined that bodies of different weights would fall at the same speed in a vacuum. By the late 14th century, scholars had significantly altered natural philosophy.

Gimpel states that the Condemnation had a stifling effect on thought; other historians, that it had no effect; but Pierre Duhem famously called 1277 “the birth-year of Science” (making 2007 Sci-

ence's 730th birthday!) Hyperbole, yes, but with a grain of truth.

Reply to Objection 3. All ancient societies forbade human dissection, save Egypt (where the Romans outlawed it). Yet, its introduction in the West at the end of the 13th century went unopposed by Church authorities. *De sepolturis* (1299) did not prohibit anatomical dissection, but the practice of boiling the flesh from Crusaders' bodies to ship the bones home cheaply. Attendance at dissections was *required* of medical students at Padua and elsewhere, and the first textbook based on dissections was Mondino de'Luzzi's *Anatomia* (1316), shortly after the bull that supposedly forbade such things. The Pope's physician, Guy de Chauliac, could hardly have written *Chirurgia magna*, a widely translated manual for dissections, if the practice were forbidden by his boss.

Every medieval reference to the earth, including those in popular sermons, calls it a sphere (e.g. Aquinas, *Summa theologiae* I.1, *Reply Obj.2*). The flat earth myth is a modern myth.

Reply to Objection 4. Galileo is the poster child precisely because he is exceptional. But he did not live in the Middle Ages and is outside the scope of these Questions. *No medieval philosopher was ever prosecuted for a conclusion in natural philosophy.*

Article 3. Whether the Middle Ages saw technological advances.

Objection 1. *It would seem otherwise because* Manchester writes that "no startling new idea or significant invention" (other than the windmill and watermill) was introduced in the entire Middle Ages.

Objection 2. Furthermore, European technological advances often originated elsewhere.

On the contrary, White says that "[t]he chief glory of the later Middle Ages was . . . the building for the first time in history of a complex civilization which rested not on the backs of sweat-

ing slaves and coolies but primarily on non-human power." And that "the four centuries following Leonardo . . . were less technologically engaged in discovering basic principles than in elaborating and refining those established during the four centuries before Leonardo."

I answer that technological progress supplied philosophers with new phenomena to ponder and accustomed society to the idea of progress. Already by the early Middle Ages innovation was conceived as an obligation from God. Hugh of St. Victor [*Didascalion*] wrote, "man's reasoning shines forth much more brilliantly by inventing these very things than ever it would have had man naturally possessed them." A tipping point was reached in the 12th century mechanical revolution. A new term appeared: *ingeniator* (engineer)—earliest citation: 1170, at Durham: *Ricardus ingeniator, vir artifiosus*.

The Latins invented deliberate technological innovation through research: They began to *envision* novelties and attempted systematically to achieve them. Some efforts were successful—the mechanical clock—other, less so—perpetual motion machines. But the *idea* of innovation became embedded in Western thought.

Robert the Englishman noted this deliberateness in 1271, when he wrote that clockmakers were "trying to invent an escapement which will move exactly as the equinoctial circle does; but they can't quite manage the job. If they could, they would have a really accurate time-piece." By the mid-14th century, Europeans were raising intricate clocks in their public squares. By the 15th century, they had invented spring-driven portable clocks. By the end of the era, pendant clocks dangled on lanyards from the necks of the wealthy.

Ingeniators were not ashamed of manual labor. Great clockmakers like Henry Bate and Giovanni de'Dondi boasted of building their clocks "*manu complevi propria*." After all, their very religion

was founded by carpenters, fishermen, and tent-makers, so they could not regard working men with the same contempt as had the ancients. Indeed, labor was accorded dignity. (A drawing by Herrad von Landsberg in her *Hortus deliciarum* shows Christ himself assisting a husband-wife plough-team.) In the towns, workingmen and their guilds enjoyed political power and the right to bear arms. This attitude proved invaluable when it came time for laboratory experiments.

Reply to Objection 1. In no particular order: camshafts, verge-and-foliot escapements, mechanical clocks, eye glasses, wheeled plows, hydraulic hammers, toothed wheels, transmission shafts, steam blowers, blast furnaces, treadles, spinning wheels, trebuchets and mangonels, crossbows, flying buttresses, stained glass, elliptical arches, cranks, overhead springs, coiled springs, horse collars, gunpowder and *pots de fer*, the mizzen mast, the compass rose, portolans, stern rudders, anaerobic curing of fatty fish ("pickled herring"), double entry bookkeeping, screw-jacks, screw presses, printing presses . . .

For information on medieval technology, see White, Gimpel, and Gies/Gies.

Reply to Objection 2. Europeans were no more inventive than others. Some of the above inventions originated elsewhere—the spinning wheel in Syria—or were independently invented elsewhere. What was new in the Latin West was not inventiveness *per se*, but its social context. "The failure of Greece and Rome to increase productivity through innovation," writes Stock, "is as notorious as the inability of historians from Gibbon to the present to account for it." Only in Europe were inventions deliberately pursued and extensively exploited as labor-saving devices—perhaps owing to the disappearance there of slavery.

The Latins didn't worry whether inventions were "permitted." While Ottoman muftis fretted over whether pub-

lic clocks were *halal* or *baram* before banning them in 1560, the Europeans built them everywhere. "No European community," says White, "felt able to hold up its head unless in its midst the planets wheeled in cycles and epicycles, while angels trumpeted, cocks crew, and apostles, kings, and prophets marched and counter-marched at the booming of the hours."

These great public clocks were not built for pious deception, like the automata in Hellenistic temples, nor, as in Byzantium and China, to enhance awe of the emperor; but—again quoting White—"were presented frankly as mechanical marvels, and the public delighted in them as such."

This delight in marvels prefigures the modern idea of "scientific progress."

Question III.

The medieval advancement of science.

Article 1. Whether medieval natural philosophers saw the world as a kind of machine and therefore sought natural explanations.

Objection 1. *It would seem otherwise, because one cannot discover natural laws if "God did it" explains everything.*

Objection 2. *Furthermore, the medievals explained actions by the object's internal nature. Glass breaks because it has a "brittle nature." But this nature can be learned only through the object's actions, and circular explanations are not explanations.*

Objection 3. *Furthermore, the medievals believed that the natural world is purposeful, and objects move to their natural ends. But purpose lies in the future and natural causes must precede their effects.*

On the contrary, Oresme [*De causa mirabilium*] writes, "I propose here . . . to show the causes of some effects which seem to be miracles and to show that the effects occur naturally . . . There is no reason to take recourse to the heavens, the last refuge of the weak, or

demons, or to our glorious God, as if he would produce these effects directly . . ." And Bishop Oresme was no slacker in theology.

I answer that the term *machina mundi*, "the machine of the world," was already common by the 12th century. And Oresme [*Livre du ciel et du monde*] used the clock metaphor three hundred years before the Scientific Revolution: "The situation [God creating the heavens and establishing their regular motions] is much like that of a man making a clock and letting it run and continue its own motion by itself . . . so that all the wheels move as harmoniously as possible."

Belief in secondary causation had, in Grant's words, "transformed Nature from a capricious and willful universe into an orderly, lawful whole accessible to the human intellect." God is the author of natural laws, the thinking went, but the laws themselves could be understood in natural terms.

Nicholas of Autrecourt argued that knowledge based on experience was uncertain because tomorrow we might have a contrary experience; but Jean Buridan responded that truth was attainable from experience "provided a *common course of nature* obtains." Conclusions could be accepted because "they have been observed true in many instances and false in none," and bizarre exceptions could be treated as exactly that.

Reply to Objection 1. William of Conches wrote, "[They say] 'We do not know how this is, but we know that God can do it.' You poor fools! God can make a cow out of a tree, but has He ever done so? Therefore show some reason why a thing is so, or cease to hold that it is so."

Aquinas wrote that reason could be applied to theology, *but revelation was forbidden to philosophy*. His insistence that faith and reason were both independent and in concord was influential.

Reply to Objection 2. To paraphrase

the objection: The formal cause of falling bodies is an inner nature called "gravity" possessed by matter, but the *nature* of gravity can only be known through the *behavior* of falling bodies. (Newton agreed [*Principia Mathematica*, *General Scholium*].) Likewise, in evolution, reproductive success is due to an inner nature called "fitness," but fitness can be known only through reproductive success. These explanations are as circular as Aristotle's brittle nature of glass, but are not discarded on those grounds.

In Aristotelian terms, the nature of an object cannot be fully known unless four *aitia* are understood. The static *aitia* (Matter and Form) explain a thing's *being*; the dynamic *aitia* (Agent and End) explain a thing's *becoming* (i.e., motion/change). Only Agent (effective cause) is a "cause" in the modern sense; so the objection is merely that formal causes are not efficient causes, which of course they are not.

The medievals recognized that extension was common to all objects, and to this they gave the name of "prime matter," which possesses dimension, but no substantial form. Substantial form actualizes prime matter to a specific nature: the form of oxygen, the form of a dog. All dogs share the substantial form of a dog, but differ in color, size, etc. These latter are called *accidental forms* or *accidents*. For details on natures and Aristotelian natural philosophy, see Wallace.

Formal causes did not disappear simply because they were disregarded any more than logic disappeared because the Renaissance deemphasized it. Now that we call them "atomic structures," "genomes," and the like, formal causes are better understood. When Feynman said, "Electrons behave . . . in exactly the same way as photons; they are both screwy, but in exactly the same way," he was recognizing that both species share a substantial form. Oxygen and carbon consist of identical matter (neutrons, protons, electrons), but possess differ-

ent natures because of their *formal* arrangements. An electron in a carbon atom does not behave as a free electron; rather, its behavior is controlled by the *form* of the carbon atom as a whole. When we say that glass breaks because of its "amorphous atomic structure," we cite a formal cause, not an efficient one. The amorphous structure doesn't *make the glass break*; it's what *makes the glass breakable*. (And we still don't know how: 3rd International Workshop on the Flow and Fracture of Advanced Glasses). Similarly, the formal cause of a dog is its "genome," while its efficient causes are the chemical and biological reactions that "unpack" and express that genome "in a manner harmonious to its environment."

The importance of "emergent properties" and "self-organization" in modern science—inherent in Aristotelian formalism—suggests that rejection of Aristotle's second *aition* may have been premature.

Reply to Objection 3. Final causes are sometimes called "purposes," but *telos* or "End" need not be consciously purposeful. A falling rock does not *intend* to minimize its gravitational potential; a species does not *plan* to become more fit for its niche; a puppy does not *strive* to become an adult dog. But each will move toward these natural ends, provided they "run true to form." Potential functions and strange attractors are teleological. Considering their importance in modern physics—and the difficulties in applying efficient causes alone to quantum entanglement—rejection of *telos* may also have been premature.

Article 2. Whether the medievals distinguished primary from secondary qualities, assigning the latter to the perceptions of the subject.

Objection 1. *It would seem they did not because the distinction derives from atomism, which Aristotle rejected as self-contradictory. The medievals held that an apple is red, or round, or tart, or*

falls with a rectilinear motion onto Newton's head without any sense that these were not all equally objective properties.

On the contrary, Oresme [*Traité du ciel et du monde*] writes, "One cannot demonstrate by any [sense] experience whatever that the heavens are moved with daily movement, because . . . if an observer is in the heavens and sees the earth clearly, the earth would seem to be moved; and if the observer were on the earth, the heavens would seem to be moved. The sight is not deceived in this, because it senses nothing except movement. But if it is relative to any such body, this judgment is made by the senses from inside that body, as Witelo stated in his *Perspectiva*; and such senses are often deceived . . ."

First, the distinction must be made. Galileo [*Il Saggiatore*] says, "tastes, odors, colors, etc., so far as their objective existence is concerned, are nothing but mere names for something which resides exclusively in our sensitive body, so that if the perceiving creatures were removed, all of these qualities would be annihilated and abolished from existence." These were called "subjective," or "secondary" qualities. Length, weight, position, etc., without which Galileo found it impossible to imagine an object, were called "objective," or "primary" qualities.

Atomism supposed that all phenomena were due to the "shape, arrangement, and motion" of identical, invisible particles. Hence, only mathematical qualities like length or weight could "really" exist in the object. Since we cannot assemble a red apple from an arrangement of colorless particles, color [and other secondary qualities] must be an effect of the extended matter on the subject's mind.

I answer that natural philosophy tried to explain the world *as perceived by humans* and this commitment to empiricism compelled scholastics to consider color, sound, etc. as real. The me-

dievals conceived *prime matter* as formless but possessing extension, that is, possessing only primary, objective qualities. They further approached subject/object duality in *perspectiva* and in nominalism.

The medieval science of *perspectiva* combined the physics of light, mirrors, and lenses with the biology of the eye and the psychology of perception. The difference between Kepler's *Optics* and Witelo's *Perspectiva*, Smith explains, lies not in their geometric analysis of image formation on the retina—identical in both books—but in that Kepler was analyzing *light* while the perspectivists were analyzing *sight*.

In Thomistic psychology, an apple's redness has real, "extensive" existence in the object. Light, by reflection, transmits the form of redness to the brain, creating an image with "intensive" existence in the subject. But extensive/intensive is not the same as objective/subjective. The medievals believed the senses were impressed by something real in the object. The apple *really* is red, and would remain red, *even if no one saw it*.

In the debate over universals, *nominalism* distinguished entities having real existence from mere names (*nomines*). *This* chair and *that* chair have real existence, but the species "chair" is only a convenient term that supposits in a sentence for any and all particular chairs. William of Ockham justified this using his famous razor to "erase" unnecessary entities, reducing them to "mere names." Galileo's claim that secondary qualities are "mere names" followed this tradition.

Atomism nudged philosophers away from Aristotle toward Plato's ideal forms; viz., abstract mathematical properties and geometric arrangements of invisible particles. This disconnected science from empiricism, making science, literally, almost sense-less. Berkeley took one step further, proposing that even *primary* qualities were subjective,

which aroused Samuel Johnson to his famous *contrapuntal* refutation. But Berkeley may have been on to something. Ask Schrödinger's cat.

Furthermore, if redness is only a subjective impression produced in the individual mind, it is impossible to speak of two people seeing the same "red." Subject/object dualism thus subverts the very idea of a knowable objective world. Yet, the simplified world of positivism, though severely battered nowadays by quantum theory, may have been necessary for the adolescence of Science.

Reply to Objection 1. The medieval realists agreed with the atomists that matter was granular, but disagreed on the nature of the granules: Their *minima naturalia* were "the least natural parts [of a body] which mingle and interact." Minimists did not make the primary/secondary distinction because their version of least particles did not require it.

Atomist particles are indivisible ("atomos"), not only in practice but in principle. They are made of identical stuff, differing only in size and shape, and do not possess the secondary qualities of the macroscopic body they comprise, such as color.

Minimist particles are *divisible*, though there is a smallest quantity of each substance *beyond which the form of the substance can not be sustained*. The minima of water is the smallest particle of water. Divided further, it ceases to be water and becomes . . . oh, let's say, hydrogen and oxygen. Minima are as different as the substances they form and do possess the secondary qualities of the macroscopic body they comprise.

If "indivisibles" have shapes, Aristotle countered, then they have parts, and are divisible, a contradiction. Indeed, modern science supports Aristotle: atoms do consist of parts: electrons, protons, and neutrons, and we have actually learned how to divide them in practice. Protons in turn are composed of quarks; and quarks are . . . When Dalton re-imagined

the atom, he argued that the atoms of different substances, e.g., gold and silver, had different properties, as the minimists had always claimed. His biggest opponents were die-hard orthodox atomists!

So, the modern concept of atom, greatly influenced by minimism, is a far cry from the identical corpuscles that forced subject/object dualism on Galileo, Descartes, and Hume. A minimist "atomic" theory might not need to separate the observer from the observed.

Article 3. Whether medieval natural philosophers used deliberate and recordable observation and experiment.

Objection 1. It would seem otherwise because Galileo [*Dialogues on the Two Chief Systems of the World*] causes Simplicio the Aristotelian to say, "You have made me see the matter so plainly and palpably, that if Aristotle's text were not contrary to it . . . I would be forced to admit it to be true." Thus, the medievals relied on texts and authorities rather than on observation of nature.

On the contrary, Pierre of Maricourt [*Epistola de magnete*] writes, "an investigator diligent in the use of his own hands . . . will in a short time correct an error which he would never do in eternity by his knowledge of natural philosophy and mathematics alone." Roger Bacon [*Opus maius*] writes, "Nature reveals herself more readily under the vexations of art than when allowed to go her own way." Likewise Albertus Magnus [*De vegetabilibus et plantis*] states, "Experiment is the only safe guide" and often adds, "I was there and saw for myself."

I answer that medieval natural philosophers were careful observers of nature and often cited *evidentia naturalis* to support their determinations, but these observations were seldom quantified and more often cited common experiences than deliberate experiments. Bacon determined that light was

faster than sound because he saw a distant blacksmith swinging a hammer before he heard the clang. Buridan's formulation of Newton's first law was inspired by his observation of a millstone that continued to roll after the gears were disengaged. But neither recorded times or distances. There were exceptions—Theodoric of Fribourg's explanation of the rainbow, Merle's weather data, astronomy in general—but for the most part, the medievals lacked the instruments needed to obtain useful measurements. Measuring distance or weight was simple, but time was problematical and temperature, force, etc. was beyond them. However, their reliance on observation was a large and important step.

Robert Grosseteste has been called the father of the experimental method. He combined the procedures of "resolution and composition" to demonstrate natural laws: First, analyze the components of a phenomenon and *induce* a principle or reason (*propter quid*); then *deduce* the logical consequences of that principle and seek evidence to verify or contradict them. This is recognizably Galileo's "demonstrative regress."

Laying the philosophical foundations for the provability of natural laws was no small thing; but Aristotelians were wary of deliberate experiments. Substances possess inner principles that inform their development "in a manner harmonious with their environment," and the purpose of Science is to understand how those forms work. By imposing artificial conditions, an experiment interferes with the natural environment and hence with understanding the principles. (For example, a genome may express itself differently under different environmental cues.)

Magicians, more interested in practical results than in hidden principles, did conduct experiments, dubbed "natural magic." ("Magic" meant that the inner principles were hidden [occult], not necessarily that they were supernatural.)

But alchemy had no academic standing, and no institutional base. When Pope John XXII called a conference of magicians and natural philosophers to ask whether magic had any foundation, the alchemists answered yes; the scientists no.

While natural philosophers reasoned about motion—often correctly—they did not apply their conclusions to the actual motions of real objects. Buridan explained motion (*L.*, momentum) by an impetus proportional to the “weight and speed” of the body—and even applied it to planetary motions; but he made no calculations for actual millstones or planets. Again, measurement was a problem: impetus theory implied that bodies in motion were heavier than at rest, but *gravitas in descendendo* could not be weighed without interfering with its speed. The alchemist-magicians, on the other hand, developed no significant interest in counting or measuring, or in making occult principles manifest. It was all rule-of-thumb. Experimental science was born of the marriage of philosophy and magic; but in the Middle Ages, they were just engaged in heavy petting.

Reply to Objection 1. Galileo was employing satire, not factual reporting. We have no record of an actual Aristotelian arguing in such a way. By Galileo’s day, rhetorical persuasion had replaced syllogistic proof as the object of reason.

Albertus Magnus [*De mineralibus*] had rebutted Galileo four hundred years early, “The aim of natural science is not simply to accept the statements of others, but to investigate the causes that are at work in nature.” Adelard of Bath, Anselm of Canterbury, and others wrote likewise, and Grosseteste, Buridan, or Oresme often modified Aristotle or called him wrong on many points. Granted, as Duhem notes, the Italian scholastics of Galileo’s day had reacted *against* the Paris school; but we mustn’t assume this applies to *medieval* scholasticism.

Scholastics could not refer readers to a source and page for an argument because hand-made books lacked consistent pagination. Rather than repeat an argument at length, they offered a quote. *The reader was expected already to know the rest.* This was as close to footnote, reference, or hyperlink as they could get, but it gives modern readers the impression of an appeal to authority.

Article 4. Whether natural philosophers used mathematics as a privileged tool for disclosing nature.

Objection 1. *It would seem not, because Aristotle warned against the use of mathematics in physics.* (The mathematical features of objects are accidental, not essential, and the behavior of objects is best explained by their essences.) And the medievals followed Aristotle in all things.

Objection 2. *Furthermore,* physics is about changing things while mathematics is about unchanging things. But principles explain the matter only if they are homogeneous with it. Therefore, following Aristotle, medievals did not use mathematics for science.

On the contrary, Robert Grosseteste wrote “nothing can be understood in natural philosophy and empirical investigation without mathematics.” By about 1320, says White, “regularity, mathematically predictable relationships, [and] facts quantitatively measurable, were looming larger in man’s picture of the universe.”

I answer that the medieval Latins pioneered the use of mathematics to *prove propositions* in physics. (This was very different from the calculation of land areas or planetary cycles.) But to do so, they faced an enormous hurdle: most Greek mathematics was unknown to them. The Romans had never translated it, having little interest in math beyond surveying [of conquered land] and accounting [of loot and booty]. “In mathematics,” writes Mahoney, “to succeed the Romans was to succeed to nothing

..." Beyond Euclid's *Elements*, little was available. Medieval scholars had to learn from scratch—and without teachers. It was all Greek to them.

Consequently, the Latins often violated Greek rules of geometry—"at times quite creatively," says Mahoney. Their purposes were practical, not theoretical: to clarify geometric references in Aristotle and elsewhere, to do the math required by the "exact sciences" (astronomy, statics, perspectiva, music), or to improve measurement instruments and practices. For example, Dominic de Clavasio [*Practica geometria*] wrote, "The ratio of the circumference of any circle to its diameter is a triple sesquiseptimate [ratio], or thereabouts, because there is no definite demonstrated ratio . . . I do not speak demonstratively, but only to teach how to find the area such that no sensible error remains." He knew π was irrational, but $22/7$ was "good enough for all practical purposes."

Aquinas had distinguished three degrees of abstraction: The **physics** of material objects is prior to the **mathematics** of ideal objects, and both are prior to and underlie the **metaphysics** of their being. Further, he distinguished qualities from their quantitative extensions, e.g., heat from temperature, raising the "exact sciences" (straddling the physics/mathematics border) to the status of Science. This eventually led to quantitative *physics*, the 14th century's radical break with Aristotle.

During the 14th century, mathematical *thinking* became embedded in natural philosophy. Oresme developed graphical displays of "longitude and latitude" (x and y), and geometrical methods for summing series and integrating linear functions, and analytical geometry stirred in its cradle. His geometrical proof of the Mean Speed Theorem was good enough that Galileo used it unchanged three hundred years later. It symbolized an important milestone: *a proposition in physics was demonstrat-*

ed by a mathematical analysis.

The medievals also introduced the *arithmetic of fractions*. Neither the Arabs nor the Latins understood Euclid's solution to irrational proportions. So the Latins created a "procedure of denomination" to convert geometric ratios into numerical ratios, and *solved the geometric problem using arithmetic*. Bradwardine devised algorithms for compound fractions to analyze Aristotle's theory of motion. (He found it contradictory.) Oresme developed a theory of commensurability of compound fractions that implicitly involved fractional exponents. (He used it to discredit astrology.)

The *continuum* was the medievals' greatest contribution to mathematical physics. It began, oddly enough, in a theological question about degrees of charity (Peter Lombard's *Sentences*, 17). Does a body participate in a constant form to varying degrees, *or does the form itself vary?* Arguing the latter, Scotus proposed that the addition of distinct similar parts to an existing form created a unified form of greater intensity. Thus, five parts of redness added to three parts of redness created eight parts of redness in exactly the same way that adding weights produced a new, increased weight. This seems obvious to us because we've had seven hundred years to get used to it; but until the "Calculators of Merton" developed this "intension and remission of forms," Aristotelian contraries had been the rule (wet/dry, hot/cold, motion/rest, etc.) Now, "either/or" could be "more-or-less."

If only they could measure them . . . But the Calculators lacked instruments to actually measure color, temperature, et al. So their mathematical treatments remained thought experiments applied to abstract problems. However, "one must conceive of measuring heat and force before one sets about doing it. If the Calculators dreamed and did not act, that does not mean their dreams were ir-

relevant to the acts of others." [Stanford *Encyclopedia of Philosophy*, on William of Heytesbury]

Reply to Objection 1. Bradwardine and others consciously departed from Aristotle when they realized that natural processes had to be represented by mathematical functions that hold for all values, and are therefore continuous.

Furthermore, to criticize the medievals both for clinging to Aristotle (as here) and for rejecting Aristotle (II.2, Obj. 2) makes it seem that the objection is really to the medievals themselves.

Reply to Objection 2. Mathematics was "about unchanging things" because arithmetic and geometry comprised all of mathematics. But after Bradwardine's compound fractions revealed logical flaws in Aristotle's theory of motion, he defined a new concept: *instantaneous motion*. Heytesbury used intension and remission of forms to develop the limit concept and open and closed sets. This laid conceptual foundations for the infinitesimal calculus, but that was as close as the medievals got to "a mathematics of changeable things."

Article 5. Whether medieval natural philosophers pursued natural philosophy as a research enterprise rather than as a body of knowledge.

Objection 1. *It would seem not, because* the Middle Ages had no sense of the natural world as a thing to be explored. Aristotle had explained everything, so nothing fundamentally new could be found.

On the contrary, John of Salisbury [*Metalogicon*] wrote, "Bernard of Chartres used to say that we are like dwarfs on the shoulders of giants, so that we can see more than they, and things at a greater distance, not by virtue of any sharpness of sight on our part, or any physical distinction, but because we are carried high and raised up by their giant size." And Fra Giordano of Pisa wrote, "Not all the arts have been found; we shall never see an end to find-

ing them." Therefore, the medievals had a sense of research and progress.

I answer that there can be no research enterprise without a defined body of knowledge in the first place. In the Latin West (and Islam), the natural sciences were organized into an Aristotelian schema that, in Peter Dear's words, "determined what was worth saying" about natural philosophy. At first, this meant understanding how particular facts "fit" into this structure; but by the 14th century, it had become clear that Aristotle's *conclusions* were sometimes wrong. Buridan at Paris, Bradwardine at Oxford, and others—working within the framework of Aristotelian *principles* and methods—had begun amending and correcting them. Meanwhile, outside the universities, *engineering* was being pursued using deliberate research.

Reply to Objection 1. Unlike *ingeniators* and magicians, university scholastics were indeed more focused on *understanding* known facts than on *discovering* new facts. Kuhn called this "normal" science (vs. "paradigm-shifting" science.) But if Aristotelian natural philosophy was essentially a taxonomic scheme, the same is true of any of its contradictory successors—positivism, instrumentalism, etc. The sense of revolution that animated 17th century science came partly from "unpacking" the consequences of these new philosophies. There was a sense of "doing something new" that Europe had not felt since . . . "unpacking" Aristotelianism in the 11th and 12th centuries.

That's why Columbus' voyages symbolize the start of the Modern Age. It wasn't the discovery of the New World that mattered. It was "the discovery of discovery."

Article 6. Whether medieval natural philosophers reconstructed the social basis of knowledge around a positive evaluation of cooperative research.

Objection 1. *It would seem other-*

wise, because the positive evaluation of cooperative research begins with The Royal Society and similar bodies.

On the contrary, Stock writes of the Middle Ages that "the same commerce that re-monetized the economy established, for the first time since antiquity, a self-conscious community of intellectuals whose uninhibited communication with each other was the necessary condition for the advancement of learning."

I answer that this new class of university scholars moved with ease from university to university. They adopted the trappings of knighthood, with titles, robes, ceremonies of initiation, and the like. People even called them "the new chivalry." But while they were in correspondence with one another, their work was essentially independent. The *peer review* used in theology to ensure orthodoxy had no counterpart in natural philosophy. Consequently, there was seldom a consensus that a Question had been "solved."

Furthermore, in the "impetus of thought," the *velocity of knowledge* counts for as much as its mass. In the manuscript culture, documents reproduced slowly and accumulated copyist errors. (Two transposed ratios in Jordanus' *Elementa super demonstrationem ponderum* muddled his explanation of the work principle.) Arguably, the greatest medieval invention was the printing press, which replaced one-off manuscripts with *proofread*, mass-produced typescripts, allowing ideas to spread more quickly.

Reply to Objection 1. In 1025, Ragimbold of Cologne and Radolf of Liege engaged in a "mathematical tournament," with other scholars participating as judges. Their letters provide the first example of the simultaneous investigation of a scientific question by different parties in contact with one another. They got it screwed up—Greek geometry was still undigested—but the remarkable thing is that it happened.

Informal groups like the Calculators

of Merton prefigured organizations like the Royal Society.

Question IV.

The medieval foundations of the Scientific Revolution.

Article 1. Whether the 17th century revolution could have occurred without the work of the late medieval natural philosophers.

Objection 1. *It would seem it could have*, because the 17th century was revolutionary to the very extent that it rejected medieval categories of thought. The Scientific Revolution occurred *in spite of*, not because of medieval scholasticism.

On the contrary, Duhem says, "the physicists of the Paris school posited the foundations of the mechanics that Galileo, his contemporaries, and his disciples developed." Copernicus repeated arguments made by Buridan and Oresme. Galileo reproduced Oresme's proof of the mean speed theorem and de Soto's law for falling weights using Bradwardine's definition of instantaneous motion. Consequently, writes Grant, "What the medieval scholastics started, their successors in the Age of Reason completed."

I answer that, Duhem's Continuity Thesis disturbed several centuries of assumptions about the Middle Ages. Not until recent times was the medieval era studied with professional dispassion; and if the continuity is not as great as Duhem contended, it is now acknowledged to be much greater than formerly supposed.

But the medieval "pre-discoveries" of modern theories noted by Duhem demonstrate continuity only in "the facts and lore" of the sciences. More crucially, the scholastics accomplished certain preconditions enabling the *methodology* of Science to develop. Following Grant, these preconditions include:

1. The independence of church and state. Charlemagne had modeled his empire on Rome, including imperial con-

trol of the priesthood. It took the papacy two centuries to secure the right to appoint bishops, preside over church councils, etc.; but by thus stripping princes of their spiritual roles, the medievals created something new: the secular state. Consequently, in the Middle Ages, *there was always another authority* to appeal to. In the social space between them, independent, freestanding institutions like guilds and universities could grow, which were elsewhere subordinate to emirs or bureaucrats.

2. **The cathedral schools** maintained Roman learning and passed it on. The Latins were "prepped" well before Aristotle's works were translated.

3. **The translations** furnished the Latin West with a ready-made curriculum that gave coherence to the study of nature. Had the medieval Church rejected pagan and Islamic learning, or had these translations been of literature and poetry, European history would have been very different—and Science perhaps never born.

4. **The universities** gave Science, for the first time in history, a home base with freedom of inquiry where the "ready-made curriculum" could be taught.

5. **The theologian-natural philosophers.** Since natural philosophy was a prerequisite for a theology degree, theologians were trained in natural philosophy and regarded it favorably.

6. **Freedom of inquiry into nature.** *Parrens scientiarum* and the administrative struggles of the arts faculties at the universities helped establish the principle. The *disputatio* and the Questions genre, which required arguments for both sides of a question, encouraged a "culture of poking into things." William of Ockham declared, "Assertions . . . concerning natural philosophy, which do not pertain to theology, should not be solemnly condemned or forbidden to anyone, since in such matters everyone should be free to say freely whatever he pleases."

7. **The maintenance and improvement of the exact sciences.** A few examples from the medieval West are: the explanation of the rainbow (Theodoric of Fribourg), the work principle in physics (anon., *Aliud commentum*), motion on an inclined plane (Jordanus de Nemours), image formation on the retina (Witelo), laws of magnetism (Pierre Maricourt), and "Gresham's" law of money (Nicole d'Oresme).

8. **The problems of science.** The Middle Ages established the subject matter of modern science: the nature of space and time, the existence of a vacuum and the possibility of motion through it, the kinematics and dynamics of local motion, etc. The scholastics posed hundreds of different questions and cited a massive amount of empirical data (bellows, siphons, etc.) Galileo and the others did not work on new questions; they found new answers. As Grant says, "Without the natural philosophy of the universities, the 17th century would have had little to discuss."

9. **The language of science.** The medievals passed along Aristotelian terms like potential, cause, matter, substance, analogy, relation, quantity and quality, genus and species, and created new terms like numerator and denominator, uniform motion, acceleration, gravity, momentum, impetus, inertia, kinematics and dynamics, intensity and quantity. Without this language, we could not talk about the problems of science.

Dear's "six innovations" of the Scientific Revolution did not pop out of nowhere. Without these medieval preconditions, a tipping point could not have occurred in the 17th century, if indeed ever. As R. R. Palmer wrote in *A History of the Modern World*, "scholastic philosophy laid foundations on which later European thought was to be reared. It habituated Europeans to great exactness, to careful distinctions, even to the splitting of hairs. It called for disciplined thinking. And it made the world safe for reason."

Reply to Objection 1. Etienne Gilson [*La Philosophie au Moyen Age*] wrote, "It is necessary . . . to relegate to the domain of legend the history of a renaissance of thought succeeding to centuries of sleep, obscurity, and error. Modern philosophy did not have to undertake the struggle to establish the rights of reason against the Middle Ages; it was, on the contrary, the Middle Ages that established them for it, and the very manner in which the seventeenth century imagined it was abolishing the work of the preceding centuries did nothing more than continue it." Galileo, Harvey, and even Newton used methods and principles that were recognizably Aristotelian.

Article 2. Whether a Scientific Revolution could have preceded the 17th century.

Objection 1. *It would seem that a scientific revolution could have occurred in the 14th century because all of the preconditions for the revolution were in place by then, and most of Dear's six transformations had at least started. By the 14th century the medievals had rethought the science of motion and introduced crucial kinematical and dynamical concepts—and the 17th century revolution occurred primarily in the science of motion.*

On the contrary, medieval natural philosophy was "holistic." It tried to explain the world *as perceived by human senses*. This was trying to explain too much, too soon. The 17th century succeeded because they restricted themselves to the simple, well-behaved domain of primary qualities, contrived experiments, and efficient causes.

I answer that the 14th century "Paris school" and "Oxford Calculators" did not between them ignite a scientific revolution. But *might* they have done so? Counterfactuals are easily imagined, less easily substantiated. History happened as it did for reasons often centuries in the making, and can seldom be altered

by changing whimsically this event or that.

What were the drivers? The medievals were devoted to reason and had separated philosophy from theology. They developed the very concept of natural laws governing a tangible universe accessible to reason. They gave science an independent home base in the universities. They conceived of qualities as measurable, applied mathematical models, and required that philosophical conclusions be "saved by the appearances" of sensory experience. Outside the universities, alchemists conducted experiments; and ingeniators engaged in deliberate research and innovation. A continent-wide network of scholars accustomed to asking probing questions about nature had begun researching non-Aristotelian theories of motion. Letter symbolism was in use, and the arithmetical operators had appeared. Subject/object duality was genuinely lacking—but an Aristotelian alternative to atomism existed that did not require it.

What were the inhibitors? The effort to explain the world as perceived by humans was biting off more than they could chew. (Imagine teaching physics and psychology as a single, combined science!) Their reliance on empiricism did not overcome their suspicion of deliberate experimentation. Their conviction that qualities were measurable awaited instruments to measure them. They applied mathematical *thinking*, but, except in the exact sciences, little mathematical *calculation*. Letter symbolism and operators were still used as shorthand in otherwise verbal discussions. Lastly, the "*velocity of knowledge*" was too slow: ideas didn't circulate fast enough to start a "chain reaction."

But if the abortive 14th century revolution came so close, why did three centuries pass before the successful 17th century version? Three factors suggest themselves. During the Renaissance, Neoplatonic idealism grew at the ex-

pense of Aristotelian empiricism, and intellectual emphasis shifted to art and literature. In the Reformation, reasoned theology retreated before personal piety. Like al-Ghazali, Luther dismissed "the whole of Aristotle." Scientifically, these eras marked time. But one additional possibility is that *there simply weren't enough people*.

At the height of the 14th century, the Black Death wiped out a third of Europe. Ockham and Bradwardine were two who perished. Populations did not recover 14th century levels until . . . the 17th century. And if the *velocity* of ideas is as important as the neutrons in an atomic pile, so is the *critical mass* of minds to emit and be excited by them. Only by Galileo's time would there again be as many natural philosophers as in Buridan's day.

Reply to Objection 1. That a "true science" is impossible within Aristotelianism stems from its conscious rejection by 16th/17th century Neoplatonists. Arguably, the Scientific Revolution was more an increased understanding of how to apply mathematics than it was a rejection of the *principles* of Aristotelian physics. The *conclusions* of Aristotelian physics are another matter—many of them were factually wrong. Yet, we do not reject *Galileo's* principles merely because he insisted on circular orbits, claimed comets were atmospheric phenomena, or cited the ocean tides as proof of the earth's rotation. In fact, Aristotle had sound empirical reasons for rejecting heliocentrism [*On physics*—perhaps even for saying that men had more teeth than women [*On animals*]. By the 14th century, Aristotelian conclusions were being questioned and corrected *within an Aristotelian framework*. Even the conceptual hurdle of deliberate experimentation might have been overcome. The "artful vexation of nature" certainly had important advocates.

The medievals did not draw the objective/subjective line in quite the same

way, and their theory of *minima naturalia* was not that of atoms; yet modern "atoms" seem much like "minimae." Heisenberg's uncertainty principle and "spooky action at a distance" have battered 17th century positivism—and resurrected 14th century ghosts. Form and telos have been making a quiet comeback under new names. "The philosophy of nature produced by authors such as Aristotle or Thomas Aquinas is perhaps less out-of-date than expected," writes Tanzella-Nitti.

So the 17th century revolution could not have happened in the 14th century. We may as well wish for the moon—which, come to think of it, is pretty much what kicked things off. But a 14th century revolution might have occurred in the 14th century, one based on *minimae*, Thomistic psychology, and all four Aristotelian *aitia*. It would have looked different than the one we got—less revolutionary, more "holistic," lacking Cartesian dualism—but must revolutions come in only one flavor?

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